Exposure to Contaminated Drinking Water and Health Disparities in North Carolina

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Objectives. To examine drinking water quality in majority Black periurban neighborhoods in Wake County, North Carolina, that are excluded from nearby municipal water service and to estimate the health benefits of extending water service.

Methods. We tested 3 samples collected July through December 2014 in 57 private wells for microbial contaminants. We compared contaminant prevalences to those in adjacent community water systems (35 280 samples from routine monitoring). Using a population intervention model, we assessed the number of annual emergency department visits for acute gastrointestinal illness that is preventable by extending water services to the 3799 residents of these periurban communities.

Results. Overall, 29.2% of 171 private well samples tested positive for total coliform bacteria and 6.43% for *Escherichia coli*, compared with 0.556% and 0.00850% of municipal system samples. An estimated 22% of 114 annual emergency department visits for acute gastrointestinal illness could be prevented by extending community water service.

Conclusions. Predominantly Black periurban neighborhoods excluded from municipal water service have poorer quality drinking water than do adjacent neighborhoods with municipal services. These disparities increase the risk of emergency department visits for acute gastrointestinal illness. (*Am J Public Health.* 2017;107:180–185. doi:10.2105/AJPH.2016.303482)

The recent Flint, Michigan, water crisis revived national attention to potential racial disparities in drinking water quality in the United States. In Flint, a change in water source intended to save money for the bankrupt city led to the corrosion of lead in water pipes and a subsequent increase in children's blood lead levels.[1] Public officials failed to respond promptly to citizen complaints and monitoring data that revealed elevated lead.[2] Thus, in Flint, operational and managerial failures led to water quality disparities.

Operational deficiencies such as those in Flint are 1 of 4 potential underlying causes of water infrastructure disparities, according to a framework proposed by VanDerslice.[3] Additional causes can include disparities in available water sources, physical infrastructure, and government policies and agencies. Although Calderon et al. described the potential for racial disparities in water quality in a review article nearly a quarter century ago,[4] few studies of such disparities have occurred since then.[3]

We examined the water quality implications of disparities in access to physical water infrastructure, 1 of the 4 potential underlying causes of water quality disparities according to VanDerslice's framework. The phenomenon we explored is the inverse of the Flint crisis. Flint residents had access to municipal water infrastructure but faced disparities because of mismanagement; we explored disparities arising from the lack of infrastructure access in Black, periurban neighborhoods of the South. Residents in these periurban southern communities are denied connections to water lines that may directly abut or even traverse their neighborhoods to serve majority White neighborhoods and rely on backyard wells for their drinking water. Often their wells are old, poorly maintained, and close to septic systems that also may have outlived their design lives, placing the wells at risk for contamination.

Previous research has documented numerous such communities throughout the southeastern United States and has ascribed the exclusion of these communities from water and other nearby municipal services to a phenomenon that demographers have termed "municipal underbounding." Demographer Charles Aiken, in a seminal 1987 article, described this phenomenon as follows:

> Whereas in metropolitan areas the majority of the black population is confined to inner cities, for many small municipalities in the South large numbers of blacks live just beyond corporate boundaries. . . . The growth of black residential areas on the fringes of municipalities has created a modern spatial dimension to race relations, especially in the struggle over political control of local governments. Frequently cities seek annexation of territory only be opposed by suburbanites. . . . For many small municipalities of the South a reverse situation has developed, for blacks in the suburban fringes seek annexation only to be resisted by white-controlled city governments.[5(p564)]

Research by Aiken, along with several more recent studies, has documented the existence of such underbounded Black communities throughout the South.[5–10]

We evaluated whether exclusion from municipal water service in underbounded neighborhoods of Wake County, North Carolina, affects drinking water quality and

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health. Specifically, we tested whether tap water samples in 57 underbounded households have higher prevalences of bacterial contaminants than do those observed in nearby municipal water systems. We then estimated the effects of bacterial contamination on the rate of emergency department (ED) visits for acute gastrointestinal illness (AGI). To our knowledge, this is the first study to examine the water quality and health implications of municipal underbounding in the American South. Two previous studies analyzed water quality in underbounded North Carolina communities but did not estimate the resulting health implications.[11] Although our study focused on North Carolina, our results may be relevant to other communities where municipal underbounding has occurred, including the Texas Lower Rio Grande and California Central valleys.[12–14]

METHODS

The study area encompassed municipal extraterritorial jurisdictions of Wake County. Under North Carolina law, municipalities can control zoning in extraterritorial jurisdictions, which may extend up to 3 miles from city boundaries, without providing municipal services (including water supply) or allowing extraterritorial jurisdiction residents to vote in municipal elections.[15]

In previous research, we used property tax records to identify Wake County extraterritorial jurisdiction census blocks in which the majority of residents lacks access to community water service.[10] We found a statistically significant negative association between Black population proportion and access to community water service: every 10% increase in Black population proportion decreased the odds of water service by 4% ($P<.05$).[10] For this study, we recruited households from majority Black extraterritorial jurisdiction census blocks lacking water service. Our previous research identified 1010 such households.

Participant Recruitment

We mailed recruitment letters to the 1010 households in majority Black extraterritorial jurisdiction census blocks without water service. The letter described the study, outlined participant obligations, offered a $25 gift card for study completion, and provided a telephone number for enrollment. Forty households responded; we recruited an additional 17 through telephone calls to homes selected at random from the 1010 addresses using a telephone list purchased from Central Address Systems, Inc.

We confirmed reliance on a private well as the primary drinking water source via telephone interview and during subsequent home visits. We also asked participants the age of their well, whether they used a septic system or were connected to a municipal sewer, and the age of their septic system (if they had one).

Water Sampling

Trained research assistants collected water samples at each house (n = 57) on 3 occasions approximately 2 months apart during July through December 2014. They drew samples from the kitchen tap (n = 47) or, when indoor access was not possible, from an outdoor spigot attached to the home (n = 10). Aseptic sampling procedures were followed: research assistants autoclaved collection bottles, washed their hands, and flushed the cold water tap for 5 minutes before sample collection. Research assistants stored samples on ice during transportation to the analytical laboratory, refrigerated them at 4°C, and analyzed them within 96 hours.

We determined total coliform, *Escherichia coli*, and *Enterococcus* fecal indicator bacteria concentrations using IDEXX Colilert and Enterolert methods in conjunction with the Quanti-Tray/2000 enumeration system, following standard method 9223.[16]

We obtained microbiological water testing results for 2006–2013 for all 309 Wake County community water systems from the North Carolina Department of Environmental Quality. From this data set, we extracted results for July through December (to coincide with the sample collection months for the private wells), yielding 35 280 samples.

We tested associations between well and septic system ages and indicator organism presence using logistic regression. We used generalized estimating equations with exchangeable correlation structures and robust SEs to account for the repeated measures. We performed analyses using the gee function in RStudio version 0.99.491 (R Foundation for Statistical Computing, Vienna, Austria).[17]

Health Impact Estimation

We estimated the AGI risks from microbial contamination in the 57 wells using a population intervention model (PIM) that we developed in our previous research.[18] Details of the PIM approach are described elsewhere.[19,20] Briefly, a PIM estimates the effects of an intervention on population health by fitting a statistical model to observed health outcomes under current conditions and then using the model to predict the change in health expected from the intervention (in this case, connecting homes to the nearest community water supply). In previous research, we developed the following PIM model of North Carolina ED visits for AGI as a function of drinking water microbiological quality[18]:

$$\begin{aligned}\ln\left(Y_{i,j}/N_i\right) &= \alpha + \beta_1 C_{\mathrm{CWS}_{i,j}} + \beta_2 E_{\mathrm{CWS}_{i,j}} + \beta_3 C_{\mathrm{DWS}_i} + \beta_4 Pov_i \\ &\quad + \beta_5 ED_i + \beta_6 I_i \\ &\quad + \left(\sum_{l=7}^{9} \beta_l R_l\right) + \left(\sum_{m=10}^{20} \beta_m t_m\right) + \mu_j,\end{aligned} \tag{1}$$

where $Y_{i,j}$ is the number of AGI ED visits in county i during month j; N_i is county population; α is a constant; $C_{\mathrm{CWS}i,j}$ and $E_{\mathrm{CWS}i,j}$ are, respectively, population proportions exposed to Safe Drinking Water Act monthly and acute microbiological water quality violations via a community water system; $C_{\mathrm{DWS}i}$ is the population proportion exposed to total coliforms in private wells; Pov_i is the population proportion in poverty; ED_i indicates whether the county has an ED; I_i indicates whether the county health uninsured rate exceeds the median North Carolina rate (16%); R_l indicates region (Coastal Plain, Piedmont, or Mountain); t_m is month; and μ_j is the error term.[18]

To estimate the avoided AGI cases if all 1010 households connected to municipal water supplies, we applied equation 1 under current conditions and under a counterfactual scenario of 100% access to municipal water (data available as a supplement to the online version of this article at http://www.ajph.org). To represent variability and uncertainty, we represented variables in equation 1 as

TABLE 1—Summary Statistics From 171 Samples of Private Wells at 57 Households in Majority Black Extraterritorial Jurisdictions: Wake County, NC, July–December 2014

Parameter	Mean ±SD	Min, Max
Total coliform concentration (n = 50) in positive samples (organisms/100 ml)	151.0 ±495.0	1.00, TNTC
Escherichia coli concentration (n = 11) in positive samples (organisms/100 ml)	17.1 ±44.2	1.00, 150.00
Enterococcus concentration (n = 19) in positive samples (organisms/100 ml)	5.8 ±16.2	1.00, 71.70
Well age (n = 44), y	32.0 ±16.0	5.00, 66.00
Septic age (n = 47), y	25.7 ±17.0	1.00, 66.00

Note. TNTC = too numerous to count.

probability distributions (Table A, available as a supplement to the online version of this article at http://www.ajph.org), and we calculated differences between scenarios via Monte Carlo simulation (10 000 iterations) using Analytica version 4.6 (Lumina Decision Systems, Los Gatos, CA).

RESULTS

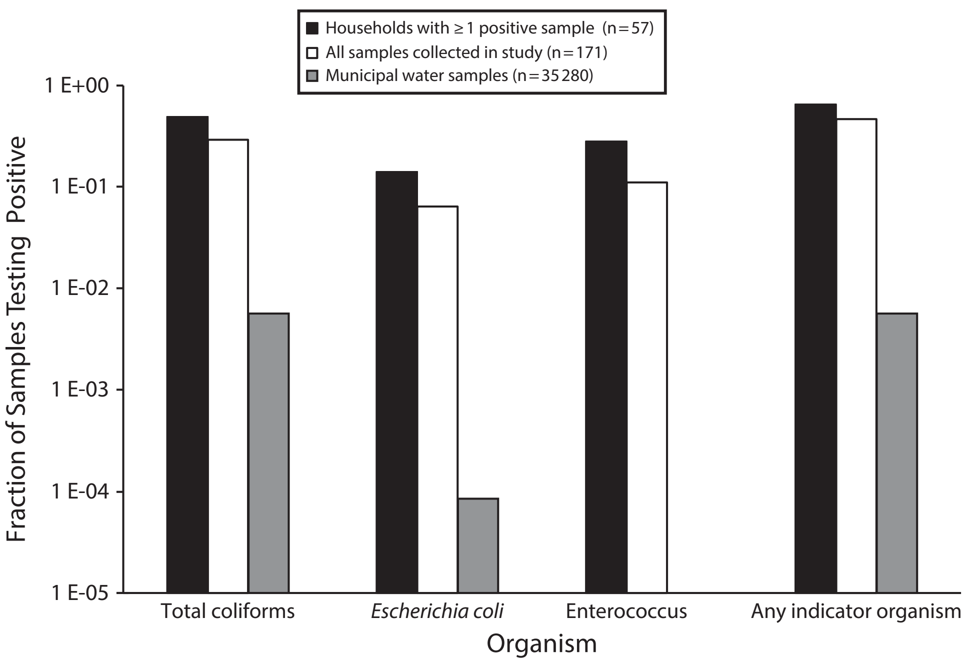
To assess drinking water quality and related health effects in underbounded communities, we recruited 57 households in Wake County neighborhoods that are unserved by nearby municipal water systems. All households lack municipal water service, but their neighborhoods are often "donut holes" surrounded by areas with water service.

The mean and median well age were 32.0 and 30.5 years, respectively (Table 1; Figure A, available as a supplement to the online version of this article at http://www.ajph.org). All but 1 of the wells were older than 6 years and as a result were not covered by a 2008 North Carolina law requiring testing of new wells on construction.[21] The mean and median septic system ages were 25.7 and 20.0 years, respectively (Table 1; Figure B, available as a supplement to the online version of this article at http://www.ajph.org). More than one third of septic systems were older than 30 years, the maximum typical septic system life expectancy.

Well Water Quality

To characterize microbiological water quality in the 57 households, we analyzed 3 samples collected at approximately 2-month intervals for 3 organisms used as indicators of fecal contamination: total coliform bacteria, *E. coli*, and *Enterococcus*. Overall, 65% of homes and 47% of samples tested positive for at least 1 organism (Figure 1).

The most prevalent indicator species was total coliforms, which was present in 49.0% of households and 29.2% of samples. *Enterococcus* and *E. coli*, which are stronger indicators of fecal contamination risk than are total coliforms, were present in 28.0% of households and 11.0% of samples and in 14.0% of households and 6.4% of samples, respectively (Figure 1). In 3 households, total coliform bacteria were detected in all 3 water samples,



Note. Municipal water samples were not tested for *Enterococcus.*

FIGURE 1—Proportion of 171 Private Well Water Samples From 57 Households Testing Positive for Indicators of Microbial Contamination Compared With Detection Rates Among Municipal Water System Samples: Wake County, NC, July–December 2014

and in 15 households these organisms were detected in 2 of the 3 samples (Figure 2).

Enterococci and *E. coli* were each detected in 2 samples in 3 of the households (Figure 2). Observed concentrations varied widely, with SDs exceeding means (Table 1). Mean (maximum) concentrations of total coliforms, *E. coli*, and Enterococci were 151.0 (too numerous to count), 17.1 (150.0), and 5.8 (71.7) organisms per 100 milliliters, respectively.

Well age was significantly ($P = .02$) associated with detection of total coliform bacteria and marginally ($P = .07$) associated with the presence of any of the 3 organisms (Table B, available as a supplement to the online version of this article at http://www.ajph.org), but associations with *E. coli* or *Enterococcus* individually were not significant. Every 1-year increase in well age increased the odds of detecting total coliforms by 3.6% (95% confidence interval [CI] = 0.039%, 7.30%). Septic system age was not significantly associated with detection of any of the organisms.

Community System Water Quality

We compared prevalences of total coliforms and *E. coli* across all 171 samples with prevalences in 35 280 samples from Wake County community water supplies. Among the community water system samples, 0.556% (n = 196) tested positive for total coliforms, and 0.00850% (3) contained *E. coli* (Figure 1). These prevalences are significantly less ($P \leq .001$) than are the prevalences of 29.2% and 6.43% for, respectively, total coliforms and *E. coli* observed in the 171 private well samples.

To estimate the potential health benefits if community water service were extended to all 3799 residents of the 1010 households in majority Black extraterritorial jurisdiction census blocks lacking water service, we applied a PIM using the total coliform test results from our study along with Wake County community water system data.[18] The model estimated that 25 ED visits per year (95% CI = 22, 29) could be avoided if these communities received drinking water of quality comparable to that in Wake County community water systems. Using data on the frequency of ED visits for AGI in Wake County from our previous research, approximately 114 such visits are expected each year among the 3799 extraterritorial jurisdiction residents. Thus, approximately 22% (95% CI = 20%, 24%) of these visits may be attributable to private well water contamination.

DISCUSSION

Our results provide evidence that neighborhoods excluded from municipal services because of underbounding on the basis of race receive drinking water of much poorer microbiological quality than do neighborhoods with community water service. In turn, residents of these neighborhoods may face an increased risk of serious gastrointestinal illness requiring treatment in an ED.

Among 171 water samples collected from 57 homes, 47% of samples and 65% of households tested positive for at least 1 of 3 microbial contaminants. As a result of the high prevalence of contamination, the risk of visiting an ED for AGI is 22% higher in these communities than in areas with community water service. These results suggest that most homeowners in such underbounded communities are not able to provide adequate management of microbial contamination risks.

To our knowledge, only 2 previous studies have tested the microbiological quality of private well water in Black extraterritorial

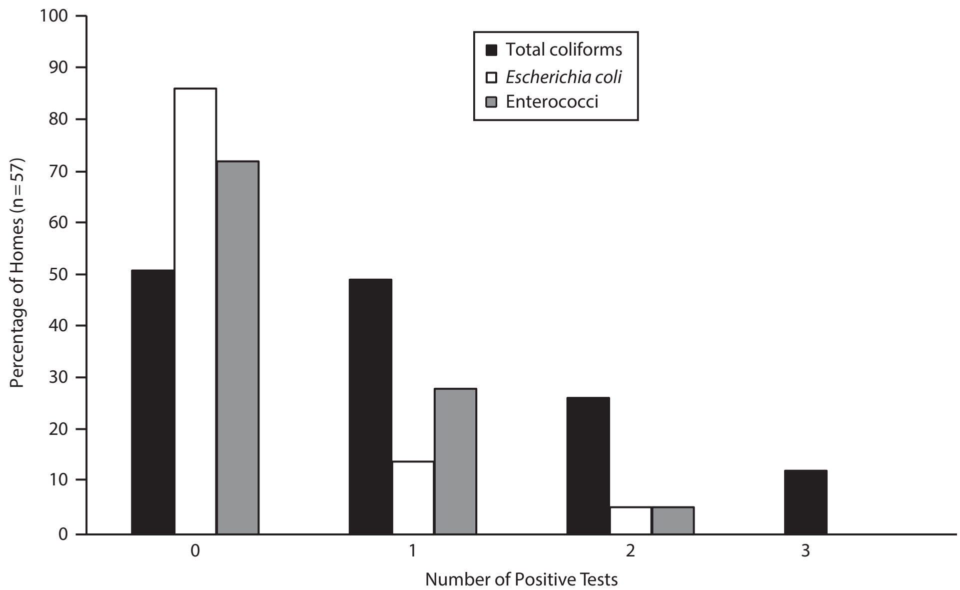


FIGURE 2—Frequency of Positive Detections of Microbial Contaminants in Private Well Water From 57 Households (3 Samples per Household): Wake County, NC, July–December 2014

jurisdictions excluded from community water service. The first study compared water quality in private wells in 3 underbounded communities bordering Mebane, North Carolina, with that in homes served by a community system; 6 of 44 wells tested positive for both fecal coliforms and *E. coli*, whereas 1 of 50 community water samples tested positive for fecal coliforms, and none tested positive for *E. coli*.[22] *E. coli* prevalence (14%) in Mebane private wells was identical to that in our study. The mean *E. coli* concentration (46/100 ml) was significantly greater ($t(14) = 1.99$; $P = .03$) than was that in our study (17.1/100 ml).

The second study sampled water from 12 private wells in an underbounded Orange County, North Carolina, community and in 8 homes served by a community water system. Results were similar to ours: 5 of 12 (41.7%) wells tested positive for fecal coliforms, similar to the 49.0% prevalence of total coliforms in our study, and 1 (8.3%) tested positive for *E. coli*, similar to the 6.4% prevalence in our study.[8] No samples from households served by municipal systems, which were located in the same neighborhood, tested positive for either of these organisms.[8]

Our water quality results are also similar to those of previous studies of rural private wells. A recent study of 2146 private well samples from rural Virginia reported that 46.0% tested positive for total coliform bacteria, comparable to the 49.0% household prevalence in our study, and 10.0% tested positive for *E. coli*, comparable to the 6.4% observed in our study.[23] Similarly, a US Geological Survey study reported an *E. coli* prevalence of 7.0% in the Blue Ridge–Piedmont geology in Virginia and a national *E. coli* private well prevalence of 7.8%.[24,25]

A Pennsylvania study found that 33.0% of rural drinking water wells tested positive for total coliforms.[26,27] A study of rural households relying on private wells in Ontario, Canada, found that 32.0% tested positive for total coliform bacteria and 24.0% were positive for *E. coli* during summer testing.[28] A study of 181 migrant farm worker camps in eastern North Carolina found that 61 (34.0%) contained total coliform bacteria, and 2 (3.3%) of these positive samples contained *E. coli*.[29]

Our estimate that 22% of ED visits for AGI are attributable to poor water quality in the population studied is similar to recent findings in a Wisconsin study of AGI risks in 14 communities served by untreated groundwater delivered by community water systems. That study used a PIM approach to estimate that 6% to 22% of AGI cases in the communities were attributable to waterborne viruses.[30]

Limitations

Several study limitations should be considered when evaluating these results. First, the sample size (57 households) was relatively small, representing 5.6% of the 1010 potentially underbounded households in Wake County. Nonetheless, this sample captured a wide distribution of extraterritorial jurisdictions of Wake County.

In addition, sampling intervals were not consistent between households but rather were determined by both homeowner schedules and geographic grouping (zip code) within the county (Figure C, available as a supplement to the online version of this article at http://www.ajph.org). An additional limitation is that grab sampling of private wells can yield inconsistent results from 1 sample to the next. Nonetheless, compared with previous studies that tested just 1 sample per well, this effect was diminished in our study because we collected 3 separate samples at different time intervals.

A final limitation is that the PIM we used to estimate health risks is on the basis of a previous North Carolina study showing a statistical association between private well water quality and ED visits for AGI,[18] but this model does not prove causation. To establish causation, information on pathogen concentrations in the well water and health outcome data specific to each member of the study population would be needed.

The measurement of pathogens and the collection of household-level health data were beyond the scope of our study. Nonetheless, previous research has indicated that the PIM approach is highly conservative compared with the approach of the Environmental Protection Agency to estimate waterborne disease risks, so the results presented here could underestimate the attributable risk.[31]

Conclusions

We found that predominantly Black communities in periurban neighborhoods historically excluded from municipal water service face disparities in the microbiological quality of their drinking water compared with adjacent neighborhoods with municipal services. These disparities, in turn, may increase the risk of serious AGI leading to ED visits.

Although resources were not available to test the chemical quality of the drinking water, the study of 12 wells in an underbounded Orange County neighborhood found elevated levels of several metals (including lead) and volatile organic compounds in some of the wells,[8] suggesting that water service disparities also could be associated with health impacts beyond AGI, such as neurotoxicity and developmental delays, which are associated with lead exposure. Further research is needed to quantify the prevalence and health impacts of chemical contaminants in these communities.

The water quality problems we observed likely result from inadequate monitoring and maintenance of wells and septic systems in these communities, tasks that may be difficult for individual households to afford. In 2008, the North Carolina General Assembly passed a law requiring the testing of all new wells constructed after July of that year. However, this law does not cover wells constructed before July 1, 2008, nor does it require or provide support for the continuous monitoring of wells, whether new or old.[21]

Our study results suggest that the lack of support for private well owners to test and maintain their wells has left underbounded communities at much greater risk of exposure to fecal contaminants in their drinking water and at increased health risk compared with adjacent communities connected to community water systems. In addition to the potential economic burden of maintaining aging private wells and septic systems, increased health risks impose costs on the affected households.

Extending public infrastructure is one way to eliminate the current disparity in water quality and health risk among underbounded communities. A previous North Carolina study of local government decision-making found that the availability of financing was the primary factor influencing decisions to extend public infrastructure to underbounded neighborhoods.[32] Financial influences on water infrastructure extension directly compete with the statutory mandate to provide the "protection of health, safety, and welfare"[15] as stated in the North Carolina Water and Sewer Authorities Act of 1971.

Unincorporated communities have struggled to obtain financial backing for infrastructure owing to local priorities, limited grant and loan funding, and challenges in data collection.[32,33] The study of North Carolina municipal decision-making also found that health risks were the least influential theme in deciding to extend infrastructure, in large part because of a lack of awareness.[32] The latter finding, along with our new results, suggests that public health practitioners have a role to play in educating elected officials about the health costs of water quality disparities and encouraging legislation that would provide funding for water service extensions to underbounded communities. As a recent *AJPH* editorial concluded,

> Their efforts may not be welcomed by elected officials and their administrative staff who will claim that public health is invading their turf. But public health practitioners can effectively insist that providing safe water distribution to homes, schools, and other consumer locations in all neighborhoods is essential and environmentally just.[34(p1359)]

Indeed, such advocacy would represent a return of public health practice to its modern foundation in advocacy of clean drinking water for all communities.[35] AJPH

CONTRIBUTORS

J. MacDonald Gibson conceptualized and designed the research and contributed substantially to the writing and editing of the article. F. Stillo oversaw participant recruitment, water sample collection, and water quality analysis and prepared the first draft of the article.

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HUMAN PARTICIPANT PROTECTION

This study was approved by the institutional review board of the University of North Carolina at Chapel Hill.

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